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Original research article

Transmittance spectrum in a 1D photonic crystal with a Fibonacci sequence composed of polymer materials

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ABSTRACT

Transmittance spectrum in a one-dimensional photonic crystal (1D-PC) composed of polystyrene (PS) and poly (methyl-methacrylate) (PMMA) materials is calculated using transfer matrix method. A photonic crystal is considered quasiperiodic with a Fibonacci sequence, and the dielectric constant of polymers is considered a function of the applied hydrostatic pressure. Numerical results indicate the presence of a photonic band gap in the transmittance spectrum with increasing Fibonacci sequence; the photonic band gap shifts to higher frequencies as the pressure increases. These gaps can be increased by increasing the Fibonacci sequence and the polymer layer thickness. Photonic band gap shifts to lower frequencies when only the material thickness is increased and the pressure and Fibonacci sequence are kept constant.

1. Introduction

Photonic crystals (PCs) are formed by intercalating materials having different dielectric constants [1,2]. These structures are characterized by their frequency ranges within which light cannot propagate [3]. These forbidden frequency transmittance spectrum ranges have zero transmittance and are known as photonic band gaps (PBGs) [4]. PCs are studied using Maxwell's macroscopic equations. Among the best known semianalytical methods for the solution of Maxwell's equations, the transfer matrix method (TMM) and the plane wave expansion (PWE) [5–10] methods are applied.

Transmittance spectrum and PBGs in PCs are tuned by modulating the dielectric constant using applied hydrostatic pressure [11–14]. By increasing the hydrostatic pressure, PBG and photonic band structure shift to higher frequencies. Semiconductors, superconductors, and polymers are commonly used to tune PBGs. Sánchez et al. [15,16] used PWE method to numerically report the shift of the photonic band structure to higher frequencies by increasing the pressure applied to a 1D PC composed of alternating PS (PMMA) and fused silica (SiO_2) layers. Further, the structure contained a defective layer and the defect mode frequency increased with compression.

This study theoretically investigates the transmittance spectrum of a quasiperiodic 1D PC having a Fibonacci sequence composed of polymeric materials. Recently, F. Segovia et al. [17] studied a quasiperiodic 1D PC composed of GaAs and $HgBa_2Ca_2Cu_3O_{8+\delta}$ layers. Results revealed that with increasing pressure and Fibonacci sequence, the oscillations in the transmittance spectrum become

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more pronounced, favoring the existence of a PBG and a shift of the cutoff frequency to higher frequencies. The model used by F. Segovia et al. [17] will be used herein when considering polystyrene (PS) and poly (methyl-methacrylate) (PMMA) layers. The remainder of this paper is organized as follows. Section 2 presents the theoretical model of the TMM. Section 3 presents the numerical results of the transmittance spectrum, and Section 4 concludes the study.

2. Theoretical model

Herein, TMM is used for calculating the transmittance spectrum in the case of normal incidence of light. In the TMM, each material of the dielectric constant ϵ_j and thickness d_j, is represented by the $M_j = \mathfrak{D}_j \mathfrak{P}_j \mathfrak{D}_j^{-1}$ matrix [6]. $\mathfrak{D}_j$ and $\mathfrak{P}_j$ represent the dynamic and propagation matrices, respectively, as follows

$$\mathfrak{D}_j = \begin{pmatrix} 1 & 1 \\ \sqrt{\epsilon_j} & -\sqrt{\epsilon_j} \end{pmatrix} \tag{1}$$

$$\mathfrak{P}_j = \begin{pmatrix} e^{i\varphi_j} & 0 \\ 0 & e^{-i\varphi_j} \end{pmatrix} \tag{2}$$

In Eq. (2), phase is represented by $\varphi_j = \frac{2\pi f d_j}{c}\sqrt{\epsilon_j}$, where c and f are the speed and frequency of light, respectively. For a structure embedded in air, the total transfer matrix is

$$\mathbf{M} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = \mathfrak{D}_a^{-1} \prod_{j=1}^{N} M_j \mathfrak{D}_0 \tag{3}$$

where $\mathfrak{D}_0$ is the dynamic matrix of air and N is the number of layers in the structure. The transmittance spectrum Γ is calculated using the matrix element m_{11} from Eq. (3) as $\Gamma = \left|\frac{1}{m_{11}}\right|^2$.

Fig. 1 shows the quasiperiodic structure of 1D PC having a Fibonacci sequence; the crystal is surrounded by air. We alternate two materials using the recursive rule $S_n = S_{(n-1)}S_{(n-2)}$ (for $n \geq 2$), with $S_0 = B$ and $S_1 = A$ [17]. The structure is assumed to have a homogeneous pattern in the xy plane, and 1D PC contains polymers. Layer B is poly (methyl-methacrylate) (PMMA), and layer A is polystyrene (PS). We consider that the dielectric constant of these polymers along the main axis (the z axis) is a function of the pressure (P) applied perpendicularly to the z axis [16],

$$\epsilon(P) = \epsilon_0 - \frac{\epsilon_0^2}{2}\left(\frac{p_{11}}{Y}(v+1)P + \frac{p_{12}}{Y}(3v+1)P\right) \tag{4}$$

where p_{11} and p_{12} are the non-zero components of Pockels tensor, Y is the Young's modulus, v is the Poisson's ratio, and ϵ_0 is the dielectric constant without pressure. Table 1 lists the values used for calculating the dielectric constants of polymers.

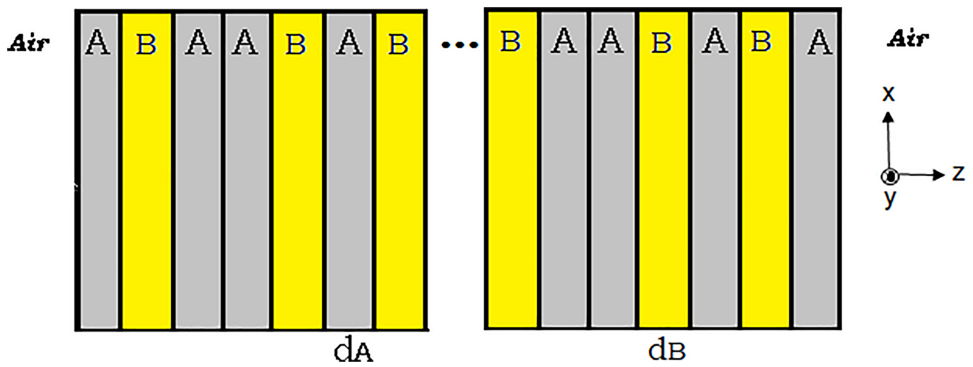

Fig. 1. Quasiperiodic structure of 1D-PC.

Table 1
Elasto-optical values for calculating the dielectric constant of polymers [15,16].

Material	Y (GPa)	v	p_{11} and p_{12}	Mean refractive index in the THz range
PMMA	3.0303	0.37	0.300 and 0.297	1.484
PS	3.3000	0.35	0.320 and 0.310	1.578

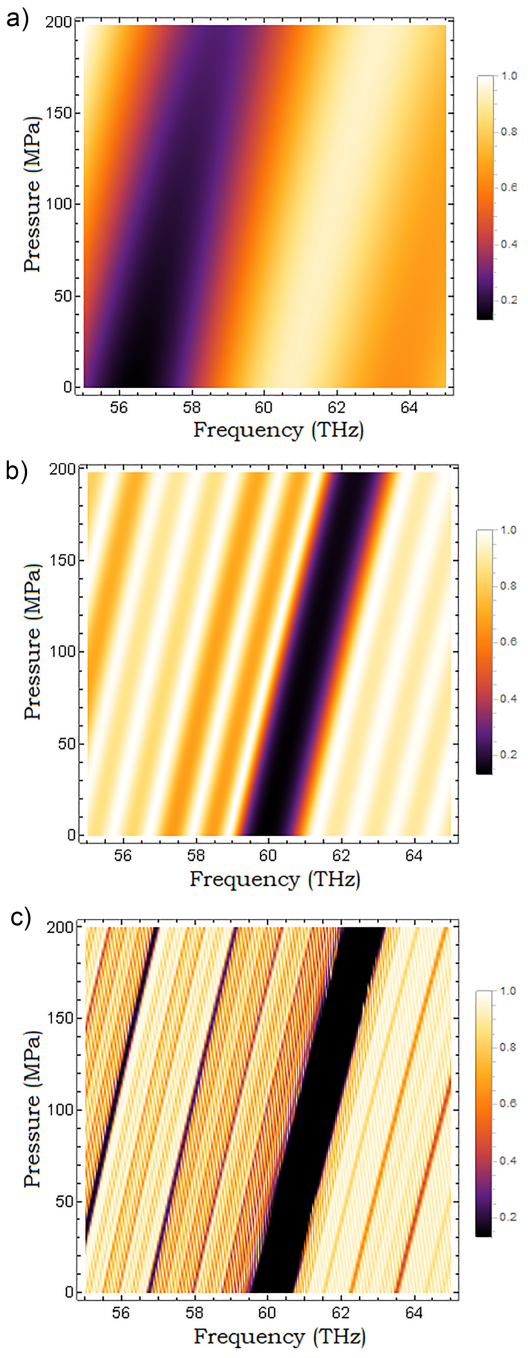

Fig. 2. Transmittance spectra as a function of pressure for different sequences S_n: (a) S_6, (b) S_{10}, and (c) S_{15}. Two layers have the same thickness $d_A = d_B = 1000$ nm.

3. Numerical results and discussion

Fig. 2 presents the numerical results derived using TMM: effects of increasing the hydrostatic pressure (from 0 to 200 MPa) and the sequences in the quasiperiodic Fibonacci in S_6 (Panel (a)), S_{10} (Panel (b)) and S_{15} (Panel (c)). In our simulations, we selected identical thicknesses for layers $d_A = d_B = 1000$ nm. By increasing the sequence S_n at fixed pressures, the transmittance spectrum displays regions wherein transmittance is zero. These regions indicate the existence of a PBG, favoring the appearance of new PBGs when the sequence S_n is increased for the 1D-PC structure. When the applied pressure is increased, the refractive index contrast decreases, causing the PBG to shift toward higher frequency regions.

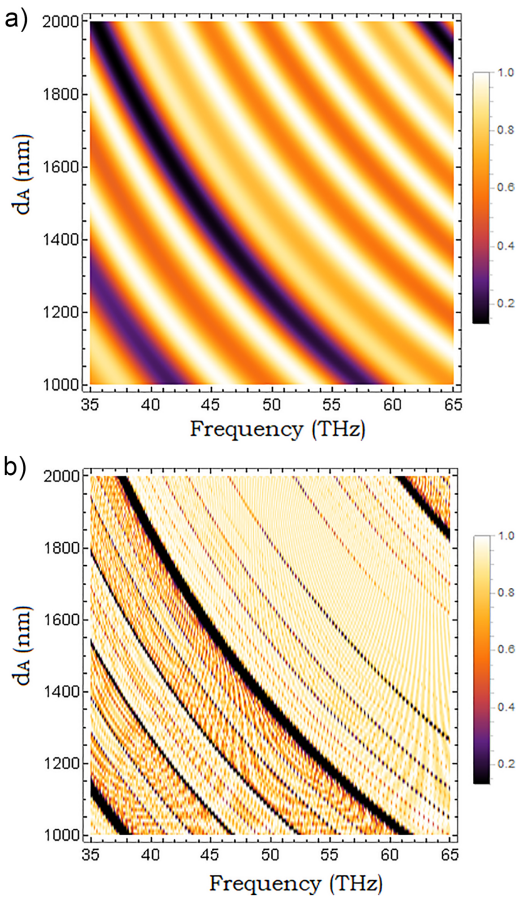

Fig. 3. Transmittance spectra as a function of d_A for different sequences S_n: (a) S_6 and (b) S_{15}. Black region represents PBG. $P = 100$ MPa and $d_B = 1000$ nm are used in simulations.

Fig. 3 shows the effects of increasing the thickness of layer A (from 1000 to 2000 nm) on the transmittance spectrum at a fixed pressure value (100 MPa) and a fixed layer B thickness (1000 nm). In Fig. 3(a), the sequence in the quasiperiodic Fibonacci is S_6. We observe that by increasing the d_A to greater than $\sim$1700 nm, the transmittance becomes almost zero between 39 and 42 THz. However, transmittance spectrum considerably changes when the sequence values of S_{15}, are increased, as shown in Fig. 3(b). In this last result, the existence of PBG is more defined, showing new PBGs in the transmittance spectrum. With increase in d_A, PBG shifts toward low-frequency regions.

A behavior similar to the one detected in the previous case is presented in Fig. 4 when the thickness of layer B is increased from 1000 to 2000 nm at a fixed pressure of 100 MPa and fixed layer A thickness of 1000 nm. In Fig. 4(a), (sequence S_6) for frequencies between 56 and 59 THz, the transmittance is $\sim$0.32. However, when the sequence S_{15} is increased, the transmittance spectrum shows the existence of four PBGs that shift to low-frequency regions with increasing d_B, as shown in Fig. 4(b).

4. Conclusions

We theoretically calculate the transmittance spectrum using TMM for a quasiperiodic 1D-PC composed of polymeric materials. The existence of PBG is controlled by increasing the Fibonacci sequence. When reviewing the dependence of the dielectric constant of materials on the applied pressure, we observe that PBG shifts toward high-frequency regions when the pressure in increased at given Fibonacci sequence and layer thickness. Additionally, when the thicknesses of layers are increased at fixed pressures and sequences, PBGs shift toward low-frequency regions in the transmittance spectrum. The increase in layer thicknesses favors the appearance of new PBGs in the transmittance spectrum.

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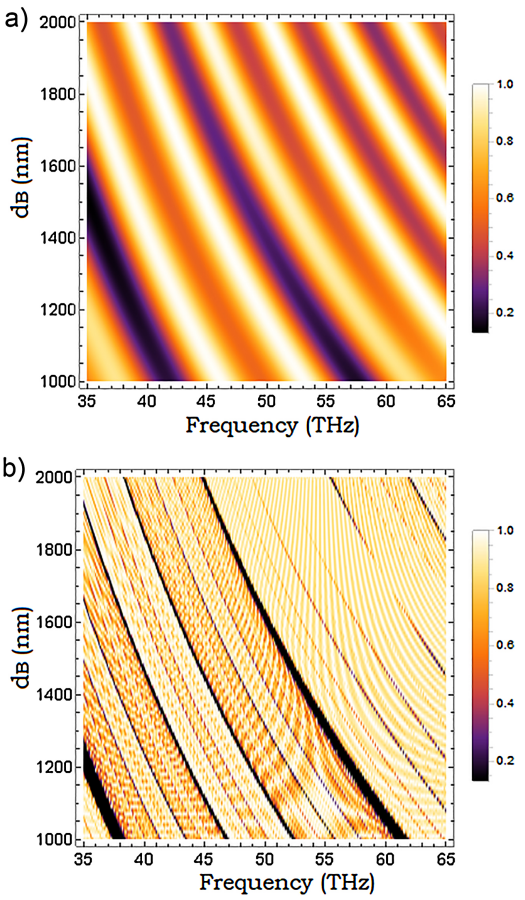

Fig. 4. Transmittance spectra as a function of d_B for different sequences S_n: (a) S_6 and (b) S_{15}. Black region represents PBG. $P = 100$ MPa, and $d_A = 1000$ nm are used in simulations.

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